

A Search for X-ray Scattering by Intergalactic Dust

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Abstract

We present the results of a search for an X-ray scattering halo around the bright, distant quasar QSO1508+5714 ($z = 4.30$) in a deep observation with *Chandra*. We set an upper limit to the density of grey, smoothly distributed intergalactic dust. The limit rules out an explanation of the SN Ia Hubble Diagram purely in terms of intergalactic extinction, and may put constraints on the cosmic dust production and dispersal rates.

Introduction

Dust in the Intergalactic Medium (IGM)

- Contains an independent record of the Global Star Formation history of the Universe
- Could affect the interpretation of the observed dimming of distant Type Ia supernovae in terms of the dynamics of the expansion of the Universe

A direct measurement of the density and properties of dust in the Intergalactic Medium is therefore important.

Detection of dust extinction in the optical/IR must rely on detection of systematic reddening with distance. This technique is only sensitive to small dust particles (particle size of order the wavelength of optical light, like the dust in our own Galaxy).

Currently, no systematic reddening to distant standard-color objects is observed: intergalactic dust must have very low density, or be 'grey' (characteristic particle size larger than a wavelength of optical light).

Large particle sizes favor the formation of an X-ray dust scattering halo. A single deep X-ray observation of a bright, distant point source turns out to be remarkably sensitive to the mass density in Intergalactic Dust. We report on a first application of this technique, which results in a preliminary upper limit on the density of Intergalactic grey dust of $\Omega_{\text{dust}} < 2 \times 10^{-6}$, too small by an order of magnitude to have an effect on the interpretation of the Hubble Diagram of SNIa.

Intergalactic X-ray Scattering Halos

Scattering of X-rays by dust is a simple classical diffraction effect. The scattering cross section scales like the fourth power of the particle size, so for given dust mass density, the optical depth to scattering increases proportionally to the particle size (bigger dust grains are easier to detect). For reasonable parameters, the Universe is marginally optically thick to dust scattering in the X-ray band.

For small optical depth $\tau_{\text{scattering}}$, the fractional halo intensity $f \equiv I_{\text{halo}}/(I_{\text{halo}} + I_{\text{unscattered}})$ is approximately equal to $f \approx \tau_{\text{scattering}}$. Calculate the scattering optical depth through the Universe by integrating

$$d\tau_{\text{scattering}} = \sigma_{\text{scattering}} n_{\text{dust}} dl \approx 6.5 \times 10^{-2} h_{75} \left(\frac{\Omega_{\text{dust}}}{10^{-5}} \right) \left(\frac{\rho}{3 \text{ g cm}^{-3}} \right) \times \left(\frac{a}{1 \mu\text{m}} \right) \left(\frac{E}{1 \text{ keV}} \right)^{-2} \frac{(1+z)^2}{E(z)} dz, \quad (1)$$

with Ω_{dust} the dust mass density in units of the critical density, h_{75} the Hubble Constant in units $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, and $E(z) \equiv \{\Omega_m(1+z)^3 + \Omega_R(1+z)^2 + \Omega_\Lambda\}^{1/2}$. a is the dust particle size, ρ the physical density of the dust grains, E is the X-ray photon energy. We have assumed a constant comoving dust density. For $z \gg 1$, assuming $\Omega_R = 0$,

$$\tau_{\text{scattering}} \approx 4.3 \times 10^{-2} \Omega_m^{-1/2} \left((1+z)^{3/2} - 1 \right) h_{75} \times \left(\frac{\Omega_d}{10^{-5}} \right) \left(\frac{\rho}{3 \text{ g cm}^{-3}} \right) \left(\frac{a}{1 \mu\text{m}} \right) \left(\frac{E}{1 \text{ keV}} \right)^{-2} \quad (2)$$

For $z \sim 4$, the fraction of scattered X-rays is $f \sim 0.44 \Omega_m^{-1/2} (\Omega_d/10^{-5}) (a/1 \mu\text{m})(\rho/3 \text{ g cm}^{-3})(E/1 \text{ keV})^{-2}$.

Figure 1 shows a simulated X-ray scattering halo, for a source at $z = 4$, with 20% of the X-rays scattered by dust of characteristic size $a \sim 1 \mu\text{m}$.

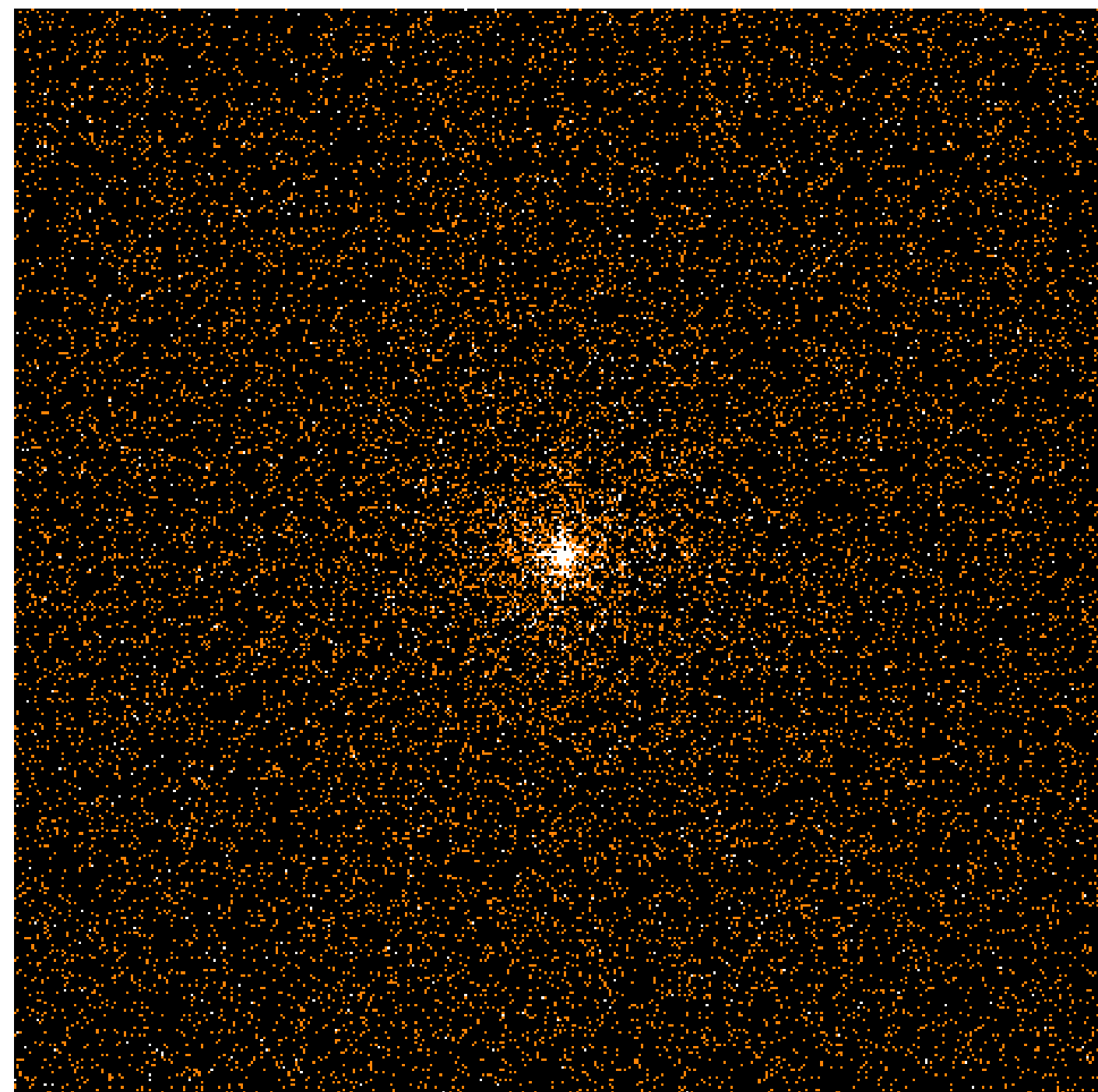


Figure 1. Simulated Chandra ACIS-S3 image, for a point source with 10,000 photons, plus a 20% scattering halo, assuming characteristic particle size $a \sim 1 \mu\text{m}$, characteristic photon energy $\sim 1 \text{ keV}$. Isotropic background appropriate for 100 ksec exposure has been added. Intensity scaling is logarithmic; pixel size is $1 \times 1 \text{ arcsec}$, field size is $8 \times 8 \text{ arcmin}$.

A Deep X-ray Image of QSO 1508+5714

The bright, distant quasar 1508 + 5714 ($z = 4.3$, $F(0.5 - 10 \text{ keV}) = 5 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$) was observed with *Chandra* ACIS/S for 100,000 sec. We detect 5400 photons from the quasar. No X-ray scattering halo is detected on the expected angular scale of $\sim 1 \text{ arcmin}$.

Figure 2 shows the *Chandra* ACIS/S3 image of the quasar; a 20% scattering halo (corresponding to an amount of dust that would be needed to explain the dimming of the SNIa) should have been visible by eye.

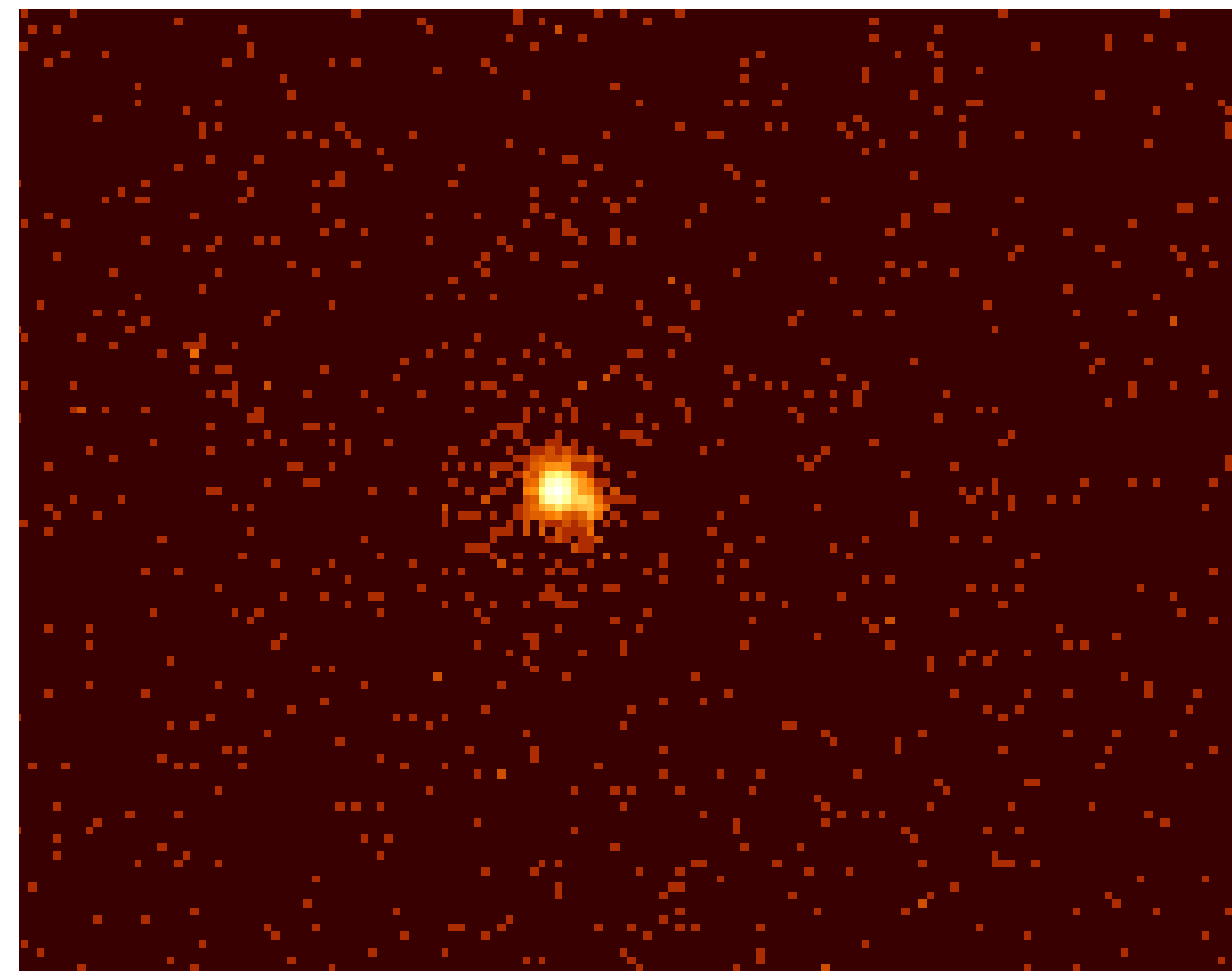


Figure 2. Chandra ACIS/S3 image of QSO1508+5714, binned in 0.5 arcsec bins, with logarithmic intensity scaling (the brightest pixel contains 1370 photons, the dimmest non-black pixels contain one photon). Image size is $1.1 \times 1.0 \text{ arcmin}$; the energy band is 0.3–8 keV. The image is slightly extended towards the Southwest, but otherwise consistent with a point source.

Results

To quantify the absence of an X-ray scattering halo, we extracted an azimuthally averaged intensity profile, subtracted the background (from a blank sky image, scaled to the same exposure time, using the same processing as for the quasar image), and compared it to the intensity profile of a nearby, bright extragalactic point source. We used 3C273 (excluding emission from the jet), whose distance is too small to produce a measurable intergalactic scattering halo. Since the core of the image of 3C273 suffers from photon pileup, we simulated the inner core with MARX for a source with the measured spectrum of QSO 1508+5714. The result is shown in Figure 3.

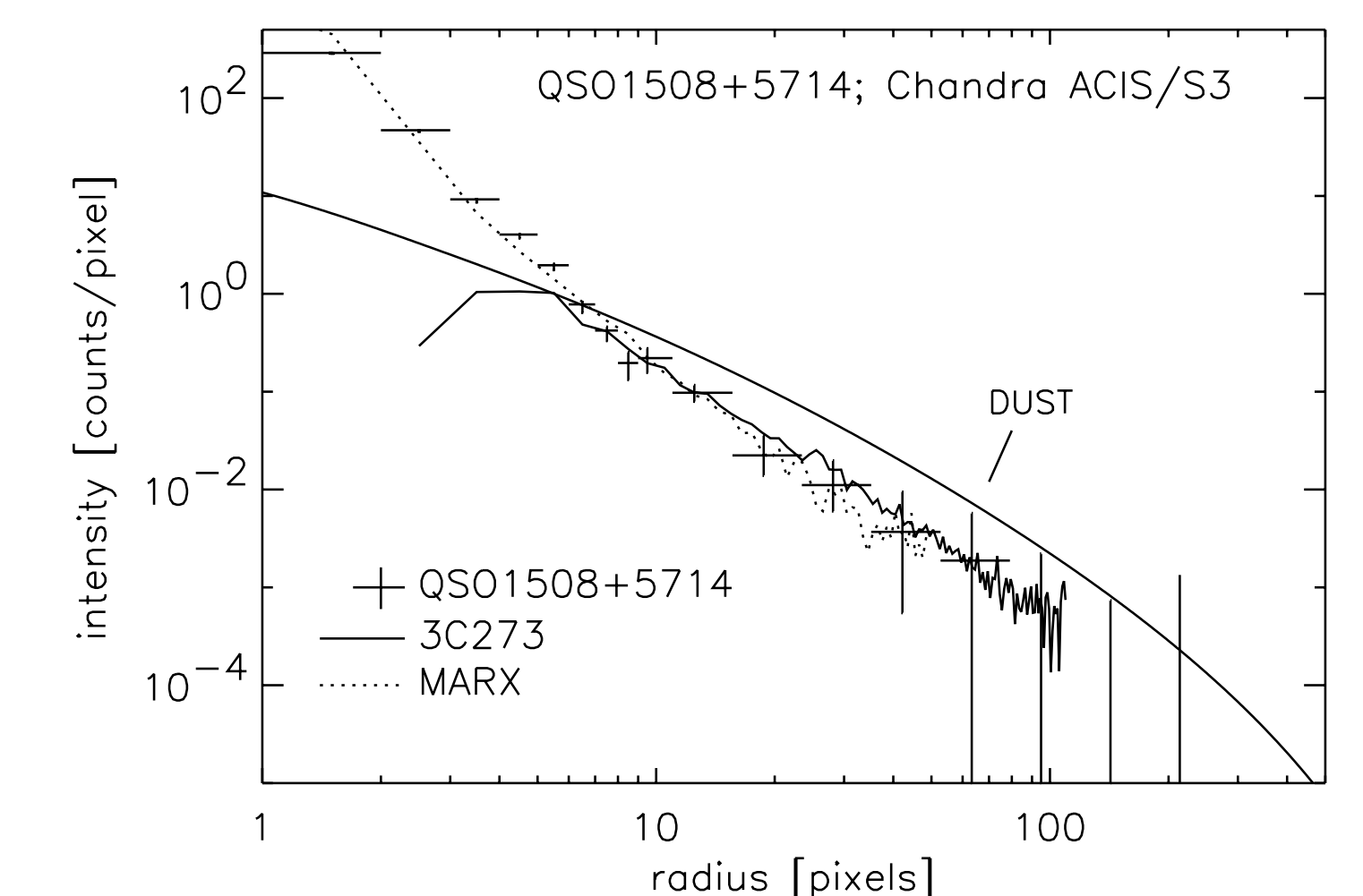


Figure 3. Azimuthally averaged intensity profile of QSO 1508+5714 (data points with error bars) as a function of the radial image coordinate (in 0.5 arcsec pixels). Overlaid is a composite point source response model, composed of the wings of the image of 3C273, and a synthetic ray trace image calculated with MARX. The profile marked 'DUST' shows the predicted intensity of a 20% halo for assumed dust particle size $a \sim 1 \mu\text{m}$, corresponding to a cosmic dust density of $\Omega_{\text{dust}} = 2 \times 10^{-6}$.

We conservatively estimate that a halo containing 20% of the point source flux should have been seen (see Figure 3).

Assuming a dust particle size of $a = 1 \mu\text{m}$ then implies **an upper limit on the density of grey intergalactic dust of $\Omega_{\text{dust}} < 2 \times 10^{-6}$** .

- This is an order of magnitude smaller than the density required to explain the dimming of SN Ia purely in terms of dust extinction.
- Estimates for the density of intergalactic dust normalized to the measured cosmic Star Formation Rate and metal production, assuming dust is expelled with an efficiency comparable to that observed in local starburst galaxies, predict dust densities $\Omega_{\text{dust}} \sim \text{few} \times 10^{-5}$. Our upper limit is roughly an order of magnitude below this level, and may therefore place interesting constraints on the cosmic dust production and dispersal rates.